



Autoencoders and Restricted Boltzmann Machines

Amir H. Payberah
payberah@kth.se
27/11/2019



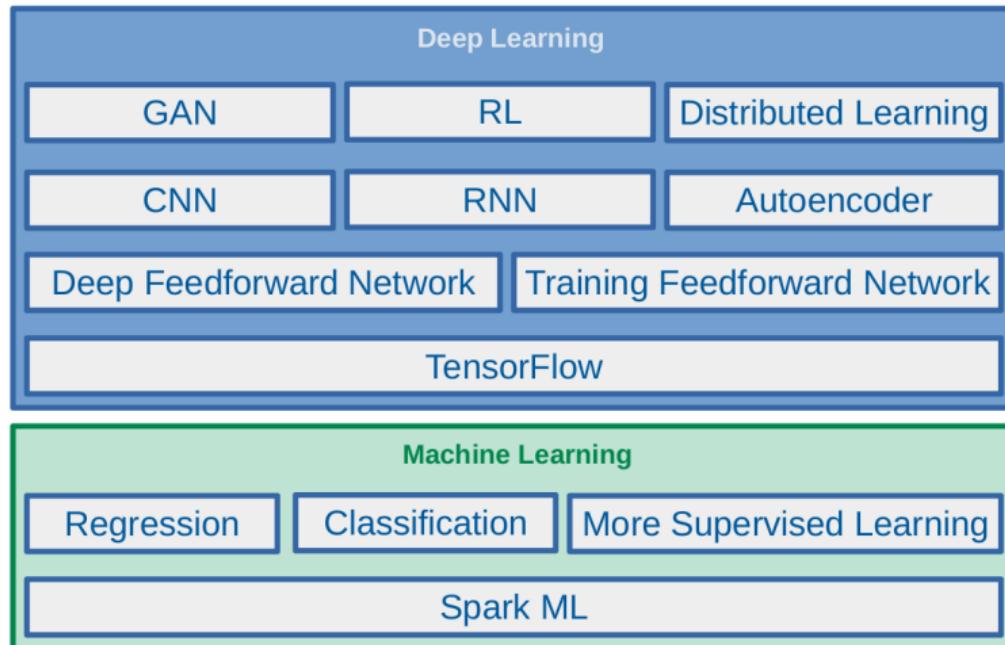


The Course Web Page

<https://id2223kth.github.io>

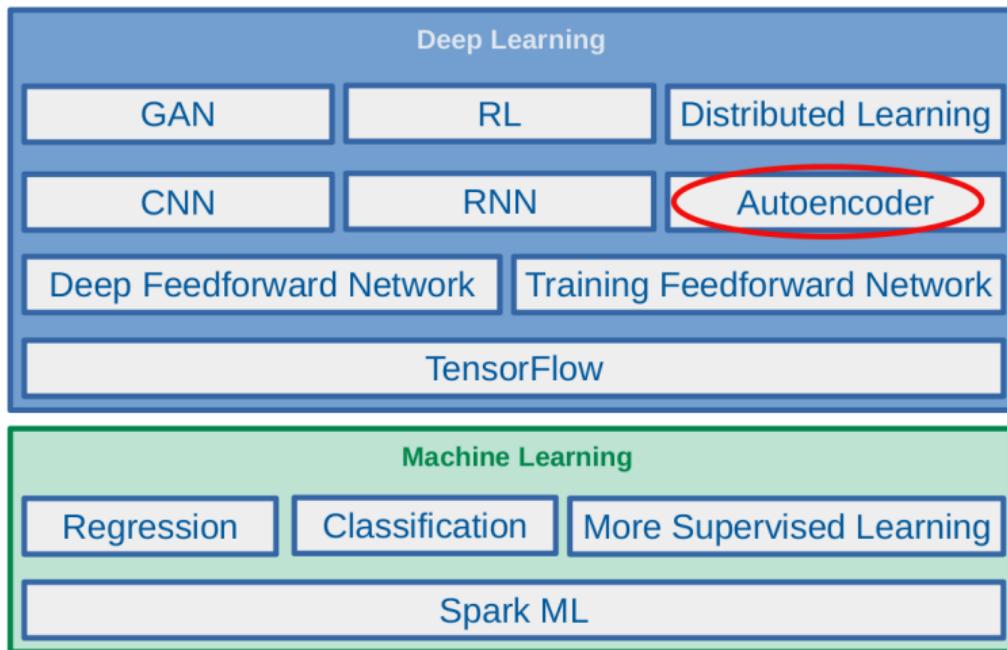


Where Are We?





Where Are We?





Let's Start With An Example



- ▶ Which of them is easier to memorize?



- ▶ Which of them is easier to memorize?
- ▶ Seq1: 40, 27, 25, 36, 81, 57, 10, 73, 19, 68



- ▶ Which of them is easier to memorize?
- ▶ Seq1: 40, 27, 25, 36, 81, 57, 10, 73, 19, 68
- ▶ Seq2: 50, 25, 76, 38, 19, 58, 29, 88, 44, 22, 11, 34, 17, 52, 26, 13, 40, 20



Seq1 : 40, 27, 25, 36, 81, 57, 10, 73, 19, 68

Seq2 : 50, 25, 76, 38, 19, 58, 29, 88, 44, 22, 11, 34, 17, 52, 26, 13, 40, 20



Seq1 : 40, 27, 25, 36, 81, 57, 10, 73, 19, 68

Seq2 : 50, 25, 76, 38, 19, 58, 29, 88, 44, 22, 11, 34, 17, 52, 26, 13, 40, 20

- ▶ Seq1 is shorter, so it should be easier.



Seq1 : 40, 27, 25, 36, 81, 57, 10, 73, 19, 68

Seq2 : 50, 25, 76, 38, 19, 58, 29, 88, 44, 22, 11, 34, 17, 52, 26, 13, 40, 20

- ▶ Seq1 is shorter, so it should be easier.
- ▶ But, Seq2 follows two simple rules:



Seq1 : 40, 27, 25, 36, 81, 57, 10, 73, 19, 68

Seq2 : 50, 25, 76, 38, 19, 58, 29, 88, 44, 22, 11, 34, 17, 52, 26, 13, 40, 20

- ▶ Seq1 is shorter, so it should be easier.
- ▶ But, Seq2 follows two simple rules:
 - Even numbers are followed by their half.
 - Odd numbers are followed by their triple plus one.



Seq1 : 40, 27, 25, 36, 81, 57, 10, 73, 19, 68

Seq2 : 50, 25, 76, 38, 19, 58, 29, 88, 44, 22, 11, 34, 17, 52, 26, 13, 40, 20

- ▶ Seq1 is shorter, so it should be easier.
- ▶ But, Seq2 follows two simple rules:
 - Even numbers are followed by their half.
 - Odd numbers are followed by their triple plus one.
- ▶ You don't need pattern if you could quickly and easily memorize very long sequences



Seq1 : 40, 27, 25, 36, 81, 57, 10, 73, 19, 68

Seq2 : 50, 25, 76, 38, 19, 58, 29, 88, 44, 22, 11, 34, 17, 52, 26, 13, 40, 20

- ▶ Seq1 is shorter, so it should be easier.
- ▶ But, Seq2 follows two simple rules:
 - Even numbers are followed by their half.
 - Odd numbers are followed by their triple plus one.
- ▶ You don't need pattern if you could quickly and easily memorize very long sequences
- ▶ But, it is hard to memorize long sequences that makes it useful to recognize patterns.



- ▶ 1970, W. Chase and H. Simon
- ▶ They observed that **expert chess players** were able to **memorize** the positions of **all** the pieces in a game by looking at the board for just **5 seconds**.



- ▶ This was only the case when the pieces were placed in **realistic positions**, not when the pieces were placed **randomly**.



- ▶ This was only the case when the pieces were placed in **realistic positions**, not when the pieces were placed **randomly**.
- ▶ Chess experts **don't have a much better memory** than you and I.



- ▶ This was only the case when the pieces were placed in **realistic positions**, not when the pieces were placed **randomly**.
- ▶ Chess experts **don't have a much better memory** than you and I.
- ▶ They just see chess **patterns more easily** due to their **experience** with the game.



- ▶ This was only the case when the pieces were placed in **realistic positions**, not when the pieces were placed **randomly**.
- ▶ Chess experts **don't have a much better memory** than you and I.
- ▶ They just see chess **patterns more easily** due to their **experience** with the game.
- ▶ **Patterns** helps them store information **efficiently**.

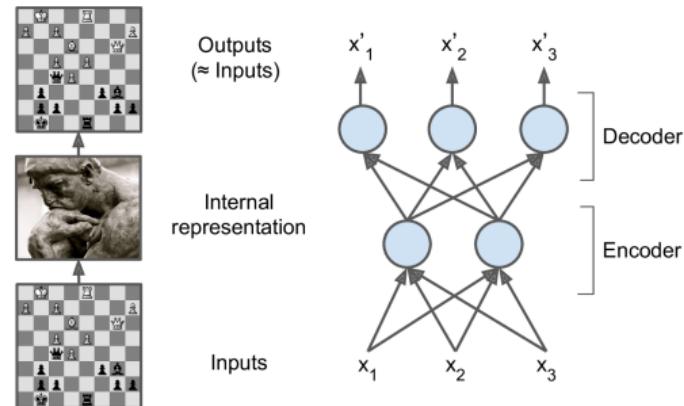




Autoencoders

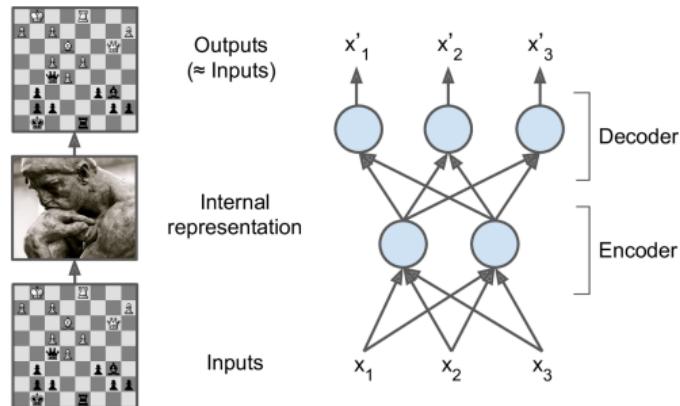
Autoencoders (1/5)

- ▶ Just like the chess players in this memory experiment.



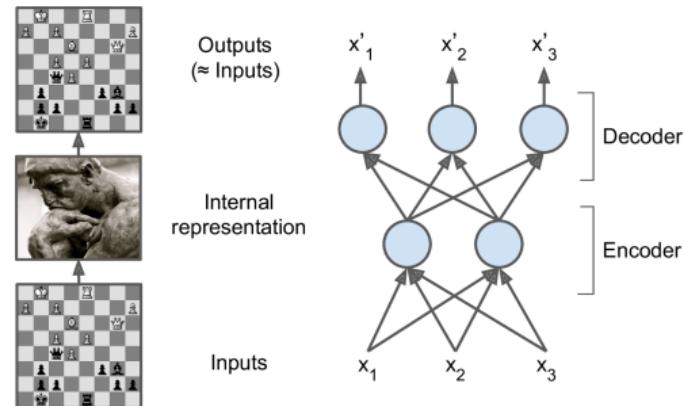
Autoencoders (1/5)

- ▶ Just like the chess players in this memory experiment.
- ▶ An **autoencoder** looks at the inputs, **converts** them to an efficient **internal representation**, and then **spits out** something that **looks very close to the inputs**.



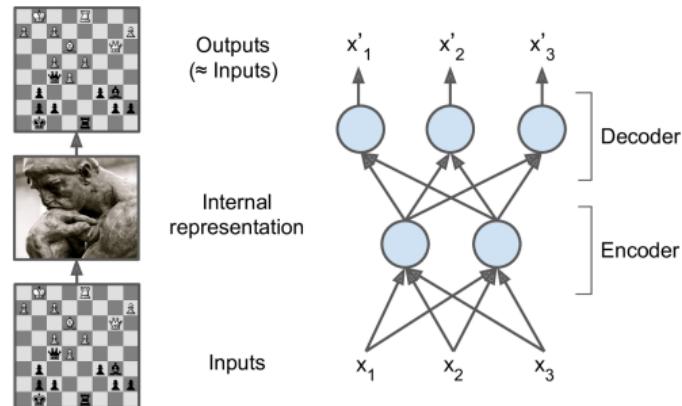
Autoencoders (2/5)

- ▶ The same architecture as a **Multi-Layer Perceptron (MLP)**.



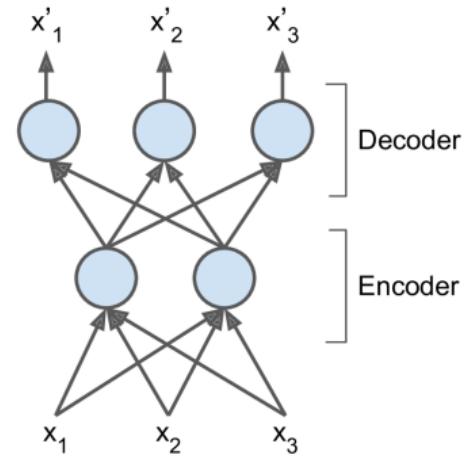
Autoencoders (2/5)

- ▶ The same architecture as a Multi-Layer Perceptron (MLP).
- ▶ Except that the number of neurons in the output layer must be **equal** to the **number of inputs**.



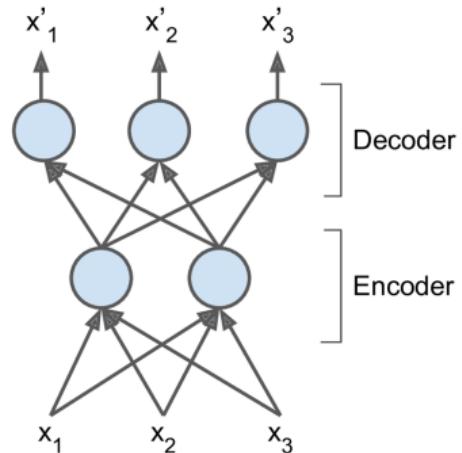
Autoencoders (3/5)

- ▶ An autoencoder is always composed of **two parts**.



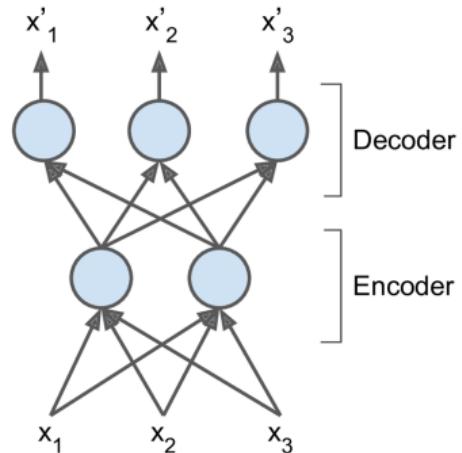
Autoencoders (3/5)

- ▶ An autoencoder is always composed of **two parts**.
- ▶ An **encoder (recognition network)**, $\mathbf{h} = f(\mathbf{x})$
Converts the **inputs** to an internal representation.



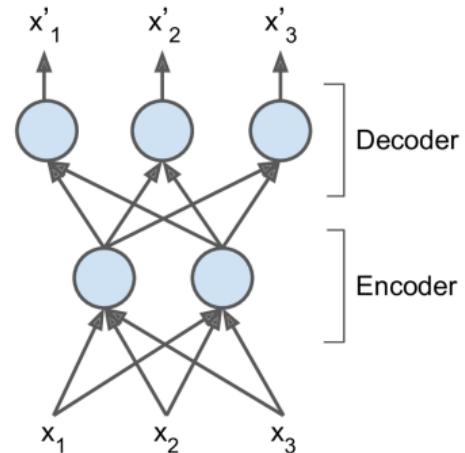
Autoencoders (3/5)

- ▶ An autoencoder is always composed of two parts.
- ▶ An encoder (recognition network), $\mathbf{h} = f(\mathbf{x})$
Converts the inputs to an internal representation.
- ▶ A decoder (generative network), $\mathbf{r} = g(\mathbf{h})$
Converts the internal representation to the outputs.



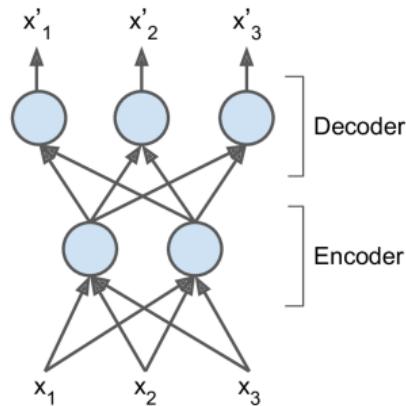
Autoencoders (3/5)

- ▶ An autoencoder is always composed of **two parts**.
- ▶ An **encoder (recognition network)**, $\mathbf{h} = f(\mathbf{x})$
Converts the **inputs** to an internal representation.
- ▶ A **decoder (generative network)**, $\mathbf{r} = g(\mathbf{h})$
Converts the **internal representation** to the **outputs**.
- ▶ If an autoencoder learns to set $g(f(\mathbf{x})) = \mathbf{x}$ everywhere, it is **not especially useful**, **why?**



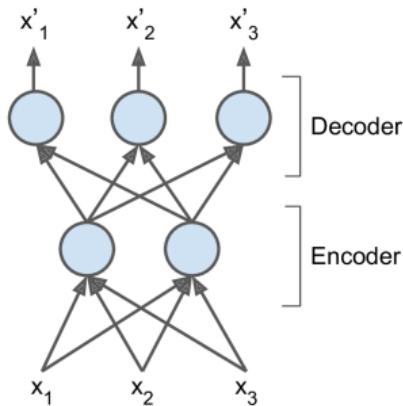
Autoencoders (4/5)

- ▶ Autoencoders are designed to be **unable** to learn to copy perfectly.



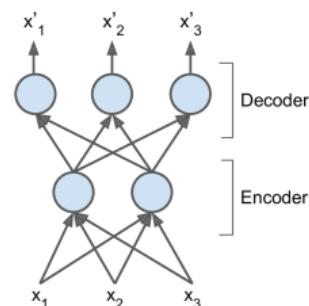
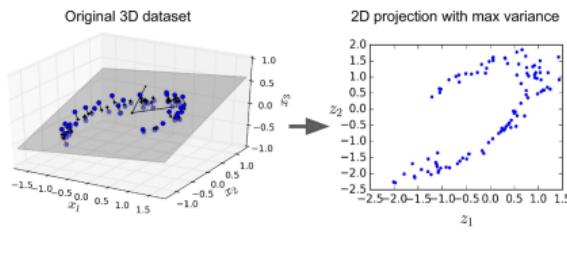
Autoencoders (4/5)

- ▶ Autoencoders are designed to be **unable** to learn to copy perfectly.
- ▶ The models are forced to **prioritize which aspects of the input** should be copied, they often learn **useful properties** of the data.



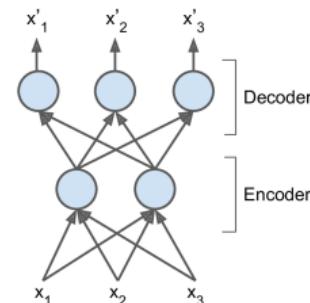
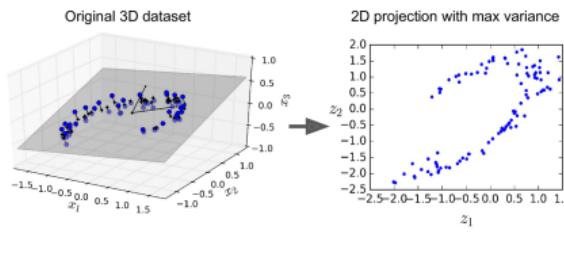
Autoencoders (5/5)

- ▶ Autoencoders are neural networks capable of learning efficient representations of the input data (called codings) without any supervision.



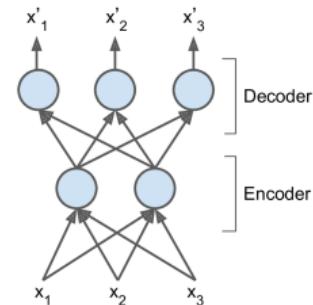
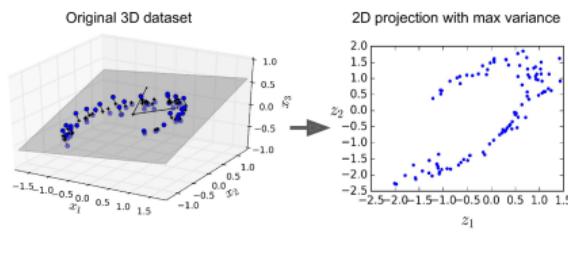
Autoencoders (5/5)

- ▶ Autoencoders are neural networks capable of learning efficient representations of the input data (called codings) without any supervision.
- ▶ Dimension reduction: these codings typically have a much lower dimensionality than the input data.



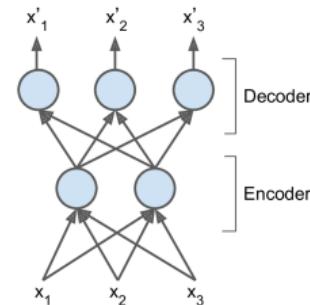
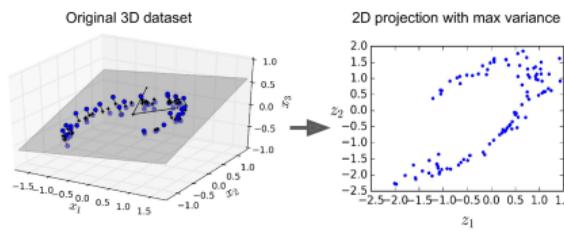
Dimension Reduction and PCA

- ▶ Principal Component Analysis (PCA) is the most popular dimensionality reduction algorithm.



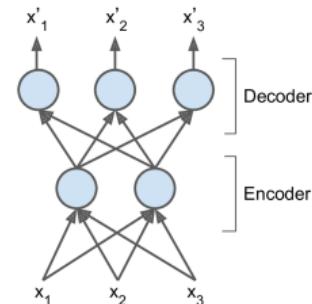
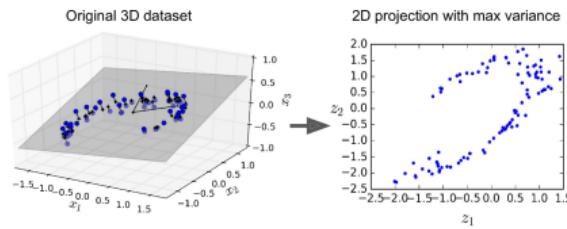
Dimension Reduction and PCA

- ▶ Principal Component Analysis (PCA) is the most popular dimensionality reduction algorithm.
- ▶ If the decoder is linear and the cost function is the Mean Squared Error (MSE), then it can be shown that it ends up performing PCA.



Dimension Reduction and PCA

- ▶ Principal Component Analysis (PCA) is the most popular dimensionality reduction algorithm.
- ▶ If the decoder is linear and the cost function is the Mean Squared Error (MSE), then it can be shown that it ends up performing PCA.
- ▶ Autoencoders with nonlinear encoder and decoder functions can thus learn a more powerful nonlinear generalization of PCA.





PCA with an Undercomplete Linear Autoencoder

- ▶ A **linear autoencoder** to perform **PCA** on a 3D dataset, projecting it to 2D.

```
n_inputs = 3  # 3D inputs
n_hidden = 2  # 2D codings
n_outputs = n_inputs
```



PCA with an Undercomplete Linear Autoencoder

- ▶ A **linear autoencoder** to perform **PCA** on a 3D dataset, projecting it to 2D.

```
n_inputs = 3  # 3D inputs
n_hidden = 2  # 2D codings
n_outputs = n_inputs
```

```
encoder = keras.models.Sequential([keras.layers.Dense(n_hidden, input_shape=[n_inputs])])
decoder = keras.models.Sequential([keras.layers.Dense(n_outputs, input_shape=[n_hidden])])
autoencoder = keras.models.Sequential([encoder, decoder])

autoencoder.compile(loss="mse", optimizer=keras.optimizers.SGD(lr=1.5))
```



Different Types of Autoencoders

- ▶ Stacked autoencoders
- ▶ Denoising autoencoders
- ▶ Variational autoencoders

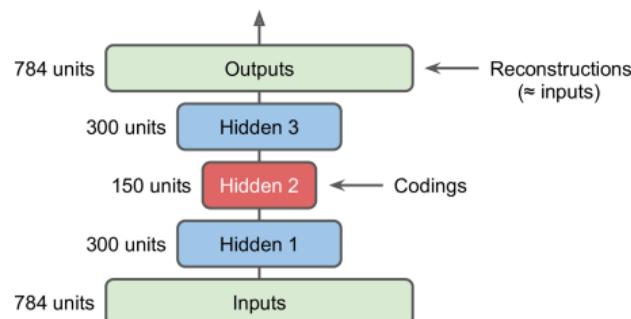


Different Types of Autoencoders

- ▶ Stacked autoencoders
- ▶ Denoising autoencoders
- ▶ Variational autoencoders

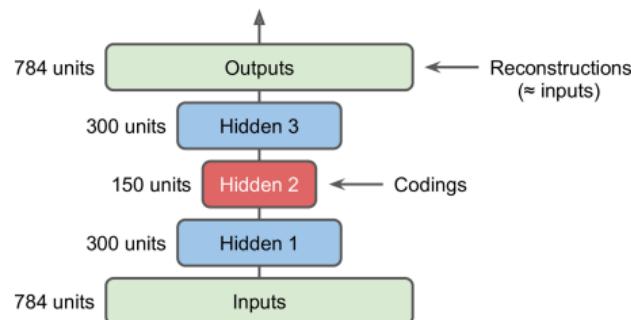
Stacked Autoencoders (1/3)

- ▶ **Stacked autoencoder**: autoencoders with **multiple hidden layers**.



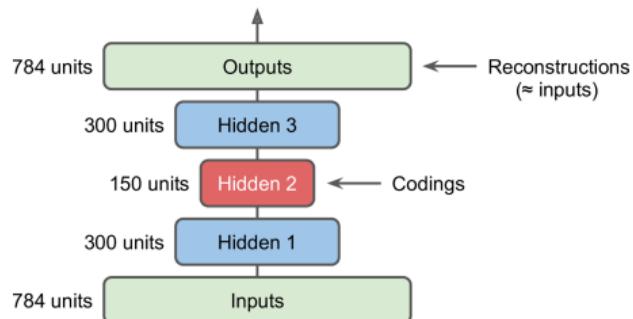
Stacked Autoencoders (1/3)

- ▶ **Stacked autoencoder**: autoencoders with **multiple hidden layers**.
- ▶ Adding **more layers** helps the autoencoder learn more **complex codings**.



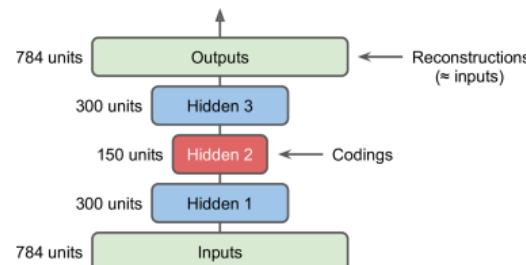
Stacked Autoencoders (1/3)

- ▶ **Stacked autoencoder**: autoencoders with **multiple hidden layers**.
- ▶ Adding **more layers** helps the autoencoder learn more **complex codings**.
- ▶ The architecture is typically **symmetrical** with regards to the **central hidden layer**.



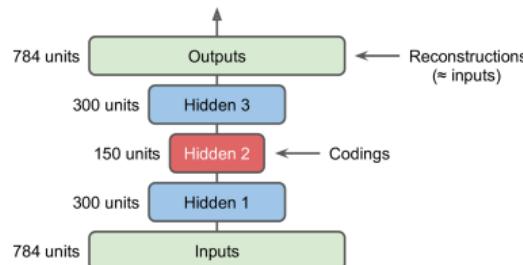
Stacked Autoencoders (2/3)

- In a symmetric architecture, we can **tie the weights** of the **decoder layers** to the weights of the **encoder layers**.



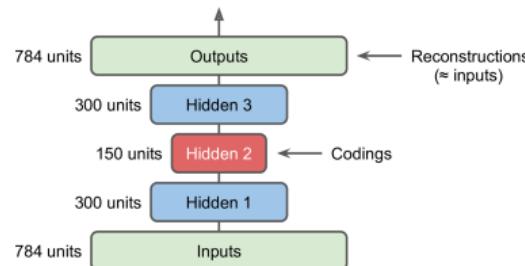
Stacked Autoencoders (2/3)

- ▶ In a symmetric architecture, we can **tie the weights** of the **decoder layers** to the weights of the **encoder layers**.
- ▶ In a network with **N** layers, the **decoder layer weights** can be defined as $w_{N-1+1} = w_1^T$, with $l = 1, 2, \dots, \frac{N}{2}$.



Stacked Autoencoders (2/3)

- ▶ In a symmetric architecture, we can **tie the weights** of the **decoder layers** to the weights of the **encoder layers**.
- ▶ In a network with **N** layers, the **decoder layer weights** can be defined as $w_{N-1+1} = w_1^T$, with $l = 1, 2, \dots, \frac{N}{2}$.
- ▶ This **halves** the **number of weights** in the model, **speeding up training** and **limiting the risk of overfitting**.





Stacked Autoencoders (3/3)

```
stacked_encoder = keras.models.Sequential([
    keras.layers.Flatten(input_shape=[28, 28]),
    keras.layers.Dense(100, activation="relu"),
    keras.layers.Dense(30, activation="relu"),
])
stacked_decoder = keras.models.Sequential([
    keras.layers.Dense(100, activation="relu", input_shape=[30]),
    keras.layers.Dense(28 * 28, activation="sigmoid"),
    keras.layers.Reshape([28, 28])
])
stacked_ae = keras.models.Sequential([stacked_encoder, stacked_decoder])
```

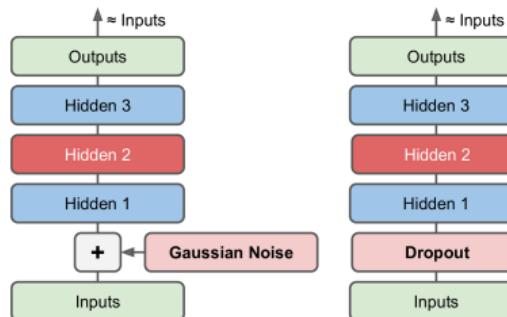


Different Types of Autoencoders

- ▶ Stacked autoencoders
- ▶ Denoising autoencoders
- ▶ Variational autoencoders

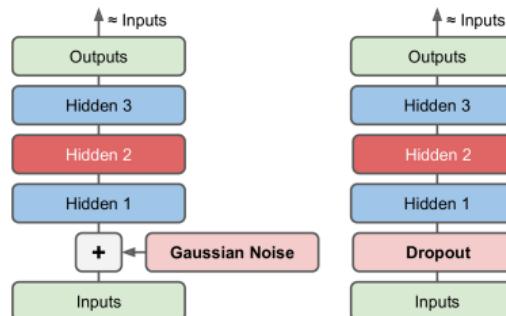
Denoising Autoencoders (1/3)

- ▶ One way to force the autoencoder to **learn useful features** is to **add noise** to its **inputs**, training it to **recover the original noise-free inputs**.



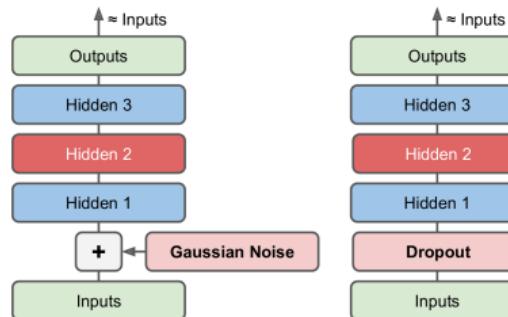
Denoising Autoencoders (1/3)

- ▶ One way to force the autoencoder to **learn useful features** is to **add noise** to its **inputs**, training it to **recover the original noise-free inputs**.
- ▶ This prevents the autoencoder from **trivially copying** its **inputs** to its **outputs**, so it ends up having to find patterns in the data.



Denoising Autoencoders (2/3)

- The noise can be pure Gaussian noise added to the inputs, or it can be randomly switched off inputs, just like in dropout.





Denoising Autoencoders (3/3)

```
denoising_encoder = keras.models.Sequential([
    keras.layers.Flatten(input_shape=[28, 28]),
    keras.layers.GaussianNoise(0.2),
    keras.layers.Dense(100, activation="relu"),
    keras.layers.Dense(30, activation="relu")
])
denoising_decoder = keras.models.Sequential([
    keras.layers.Dense(100, activation="relu", input_shape=[30]),
    keras.layers.Dense(28 * 28, activation="sigmoid"),
    keras.layers.Reshape([28, 28])
])
```



Different Types of Autoencoders

- ▶ Stacked autoencoders
- ▶ Denoising autoencoders
- ▶ Variational autoencoders



Variational Autoencoders (1/3)

- ▶ Variational autoencoders are probabilistic autoencoders.



Variational Autoencoders (1/3)

- ▶ Variational autoencoders are probabilistic autoencoders.
- ▶ Their outputs are partly determined by chance, even after training.
 - As opposed to denoising autoencoders, which use randomness only during training.

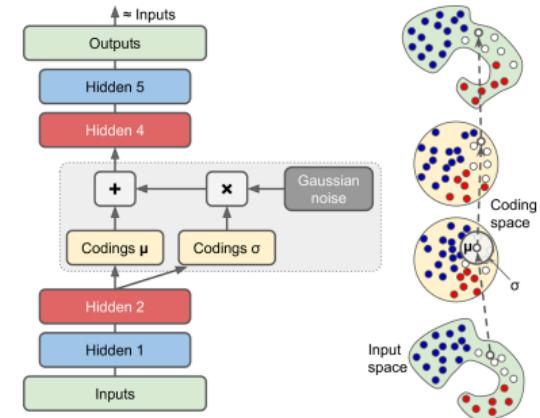


Variational Autoencoders (1/3)

- ▶ Variational autoencoders are probabilistic autoencoders.
- ▶ Their outputs are partly determined by chance, even after training.
 - As opposed to denoising autoencoders, which use randomness only during training.
- ▶ They are generative autoencoders, meaning that they can generate new instances that look like they were sampled from the training set.

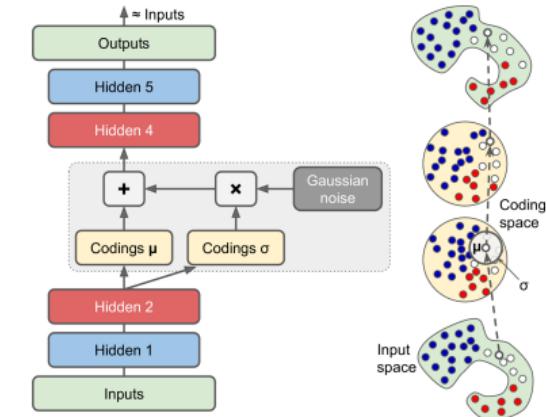
Variational Autoencoders (2/3)

- ▶ Instead of directly producing a coding for a given input, the **encoder** produces a **mean coding μ** and a **standard deviation σ** .



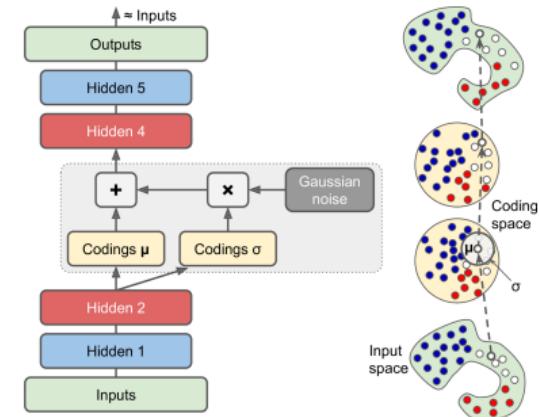
Variational Autoencoders (2/3)

- ▶ Instead of directly producing a coding for a given input, the **encoder** produces a **mean coding μ** and a **standard deviation σ** .
- ▶ The **actual coding** is then **sampled randomly** from a **Gaussian distribution** with mean μ and standard deviation σ .



Variational Autoencoders (2/3)

- ▶ Instead of directly producing a coding for a given input, the **encoder** produces a **mean coding μ** and a **standard deviation σ** .
- ▶ The **actual coding** is then **sampled randomly** from a **Gaussian distribution** with mean μ and **standard deviation σ** .
- ▶ After that the **decoder** just **decodes** the sampled coding normally.





Variational Autoencoders (3/3)

- ▶ The **cost function** is composed of **two parts**.



Variational Autoencoders (3/3)

- ▶ The **cost function** is composed of **two parts**.
- ▶ 1. the usual **reconstruction loss**.
 - Pushes the autoencoder to **reproduce its inputs**.
 - Using **cross-entropy**.



Variational Autoencoders (3/3)

- ▶ The **cost function** is composed of **two parts**.
- ▶ 1. the usual **reconstruction loss**.
 - Pushes the autoencoder to **reproduce its inputs**.
 - Using **cross-entropy**.
- ▶ 2. the **latent loss**
 - Pushes the autoencoder to have **codings** that look as though they were **sampled from a simple Gaussian distribution**.



Variational Autoencoders (3/3)

- ▶ The **cost function** is composed of **two parts**.
- ▶ 1. the usual **reconstruction loss**.
 - Pushes the autoencoder to **reproduce its inputs**.
 - Using **cross-entropy**.
- ▶ 2. the **latent loss**
 - Pushes the autoencoder to have **codings** that look as though they were **sampled from a simple Gaussian distribution**.
 - Using the **KL divergence** between the **target distribution** (the Gaussian distribution) and the **actual distribution** of the codings.



Variational Autoencoders (3/3)

- ▶ The **cost function** is composed of **two parts**.
- ▶ 1. the usual **reconstruction loss**.
 - Pushes the autoencoder to **reproduce its inputs**.
 - Using **cross-entropy**.
- ▶ 2. the **latent loss**
 - Pushes the autoencoder to have **codings** that look as though they were **sampled from a simple Gaussian distribution**.
 - Using the **KL divergence** between the **target distribution** (the Gaussian distribution) and the **actual distribution** of the codings.
 - KL divergence measures the **divergence between the two probabilities**.



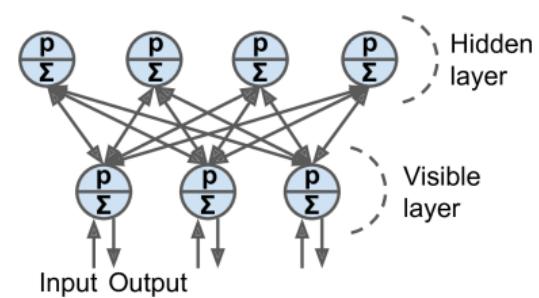
Original illustration: Sonia Jerrems



Restricted Boltzmann Machines

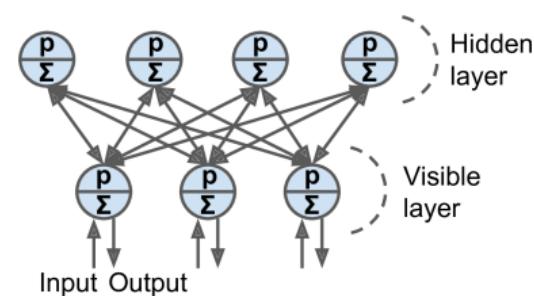
Restricted Boltzmann Machines

- A Restricted Boltzmann Machine (RBM) is a stochastic neural network.



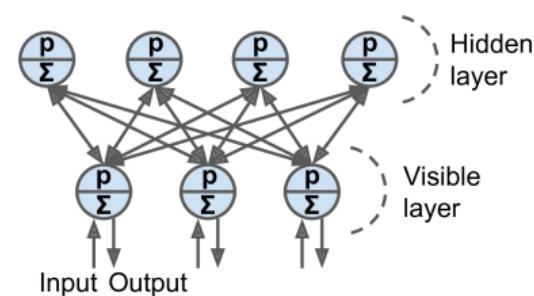
Restricted Boltzmann Machines

- ▶ A Restricted Boltzmann Machine (RBM) is a stochastic neural network.
- ▶ Stochastic meaning these activations have a probabilistic element, instead of deterministic functions, e.g., logistic or ReLU.



Restricted Boltzmann Machines

- ▶ A Restricted Boltzmann Machine (RBM) is a stochastic neural network.
- ▶ Stochastic meaning these activations have a probabilistic element, instead of deterministic functions, e.g., logistic or ReLU.
- ▶ The neurons form a bipartite graph:
 - One visible layer and one hidden layer.
 - A symmetric connection between the two layers.
 - There are no connections between neurons within a layer.





Let's Start With An Example

RBM Example (1/10)

- We have a set of **six movies**, and we ask users to tell us which ones **they want to watch**.



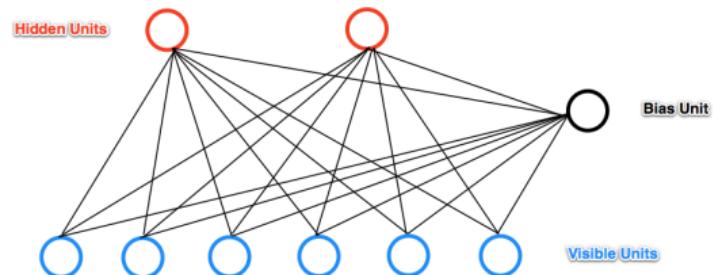
RBM Example (1/10)

- ▶ We have a set of **six movies**, and we ask users to tell us which ones **they want to watch**.
- ▶ We want to learn two **latent neurons (hidden neurons)** underlying movie preferences, e.g., **SF/fantasy** and **Oscar winners**



RBM Example (2/10)

- ▶ Our RBM would look like the following.



RBM Example (3/10)

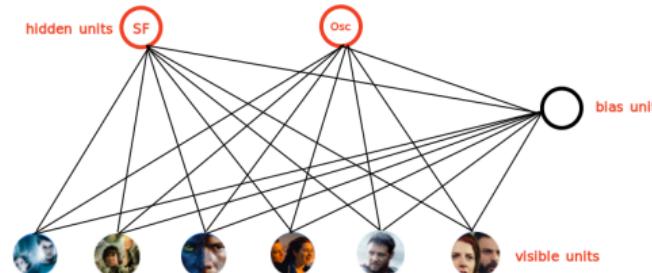
- ▶ Assume the given input x_i is the 0 or 1 for each visible neuron v_i .
 - 1: like a movie, and 0: dislike a movie



RBM Example (3/10)

- ▶ Assume the given input x_i is the 0 or 1 for each visible neuron v_i .
 - 1: like a movie, and 0: dislike a movie
- ▶ Compute the activation energy at hidden neuron h_j :

$$a(h_j) = \sum_i w_{ij} v_i$$

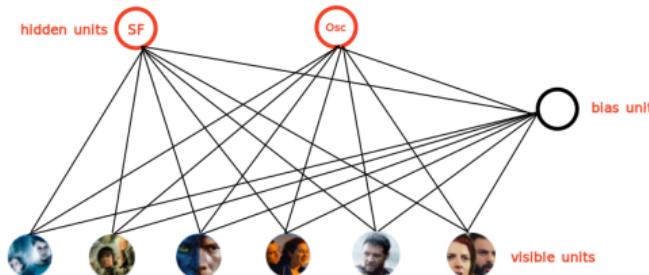


RBM Example (4/10)

- ▶ For each hidden neuron h_j , we compute the probability $p(h_j)$.

$$a(h_j) = \sum_i w_{ij} v_i$$

$$p(h_j) = \text{sigmoid}(a(h_j)) = \frac{1}{1 + e^{-a(h_j)}}$$



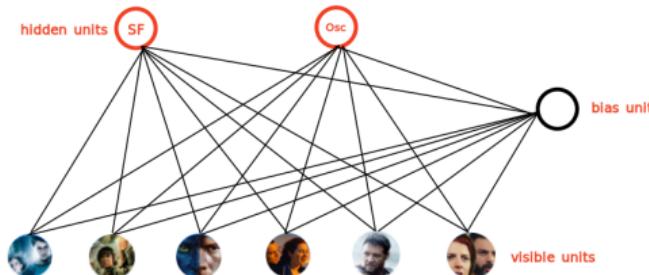
RBM Example (4/10)

- ▶ For each hidden neuron h_j , we compute the probability $p(h_j)$.

$$a(h_j) = \sum_i w_{ij} v_i$$

$$p(h_j) = \text{sigmoid}(a(h_j)) = \frac{1}{1 + e^{-a(h_j)}}$$

- ▶ We turn on the hidden neuron h_j with the probability $p(h_j)$, and turn it off with probability $1 - p(h_j)$.



RBM Example (5/10)

- ▶ Declaring that you like Harry Potter, Avatar, and LOTR, doesn't guarantee that the SF/fantasy hidden neuron will turn on.



RBM Example (5/10)

- ▶ Declaring that you like Harry Potter, Avatar, and LOTR, doesn't guarantee that the SF/fantasy hidden neuron will turn on.
- ▶ But it will turn on with a high probability.



RBM Example (5/10)

- ▶ Declaring that you like Harry Potter, Avatar, and LOTR, doesn't guarantee that the SF/fantasy hidden neuron will turn on.
- ▶ But it will turn on with a high probability.
 - In reality, if you want to watch all three of those movies makes us highly suspect you like SF/fantasy in general.
 - But there's a small chance you like them for other reasons.





RBM Example (6/10)

- ▶ Conversely, if we know that one person **likes SF/fantasy** (so that the SF/fantasy **neuron is on**)



RBM Example (6/10)

- ▶ Conversely, if we know that one person **likes SF/fantasy** (so that the SF/fantasy **neuron is on**)
- ▶ We can ask the RBM to generate a set of **movie recommendations**.

RBM Example (6/10)

- ▶ Conversely, if we know that one person **likes SF/fantasy** (so that the SF/fantasy **neuron is on**)
- ▶ We can ask the RBM to generate a set of **movie recommendations**.
- ▶ The **hidden neurons** send messages to the **visible (movie) neurons**, telling them to **update their states**.

$$a(v_i) = \sum_j w_{ij} h_j$$

$$p(v_i) = \text{sigmoid}(a(v_i)) = \frac{1}{1 + e^{-a(v_i)}}$$



RBM Example (6/10)

- ▶ Conversely, if we know that one person **likes SF/fantasy** (so that the SF/fantasy **neuron is on**)
- ▶ We can ask the RBM to generate a set of **movie recommendations**.
- ▶ The **hidden neurons** send messages to the **visible (movie) neurons**, telling them to **update their states**.

$$a(v_i) = \sum_j w_{ij} h_j$$

$$p(v_i) = \text{sigmoid}(a(v_i)) = \frac{1}{1 + e^{-a(v_i)}}$$

- ▶ Being on the **SF/fantasy** neuron **doesn't guarantee** that we'll always recommend all three of **Harry Potter**, **Avatar**, and **LOTR**.



RBM Example (6/10)

- ▶ Conversely, if we know that one person **likes SF/fantasy** (so that the SF/fantasy **neuron is on**)
- ▶ We can ask the RBM to generate a set of **movie recommendations**.
- ▶ The **hidden neurons** send messages to the **visible (movie) neurons**, telling them to **update their states**.

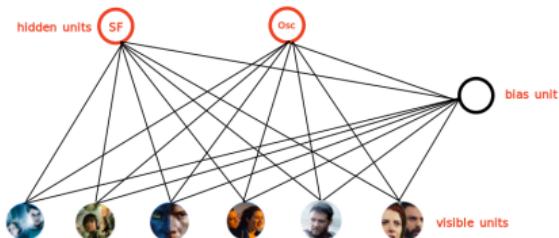
$$a(v_i) = \sum_j w_{ij} h_j$$

$$p(v_i) = \text{sigmoid}(a(v_i)) = \frac{1}{1 + e^{-a(v_i)}}$$

- ▶ Being on the **SF/fantasy** neuron **doesn't guarantee** that we'll always recommend all three of **Harry Potter**, **Avatar**, and **LOTR**.
 - For example **not everyone** who likes science fiction liked Avatar.

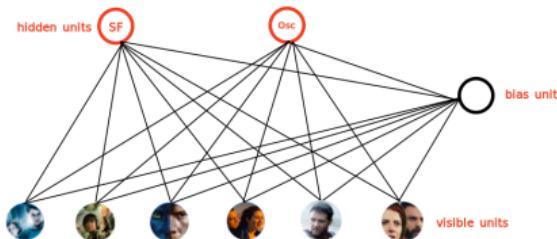
RBM Example (7/10)

- ▶ How do we **learn** the **connection weights** w_{ij} in our network?



RBM Example (7/10)

- ▶ How do we **learn** the **connection weights** w_{ij} in our network?
- ▶ Assume, as an input we have a bunch of **binary vectors x** with **six elements** corresponding to a **user's movie preferences**.



RBM Example (7/10)

- ▶ How do we **learn** the **connection weights** w_{ij} in our network?
- ▶ Assume, as an input we have a bunch of **binary vectors x** with **six elements** corresponding to a **user's movie preferences**.
- ▶ We do the **following steps** in each **epoch**:



RBM Example (7/10)

- ▶ How do we **learn** the **connection weights** w_{ij} in our network?
- ▶ Assume, as an input we have a bunch of **binary vectors x** with **six elements** corresponding to a **user's movie preferences**.
- ▶ We do the **following steps** in each **epoch**:
- ▶ 1. Take a **training instance x** and set the **states** of the **visible neurons** to these preferences.



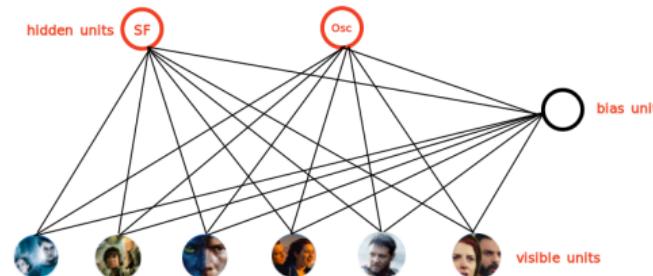
RBM Example (8/10)

- ▶ 2. Update the **states** of the **hidden neurons**.



RBM Example (8/10)

- ▶ 2. Update the **states** of the **hidden neurons**.
 - Compute $a(h_j) = \sum_i w_{ij}v_i$ for each **hidden neuron** h_j .



RBM Example (8/10)

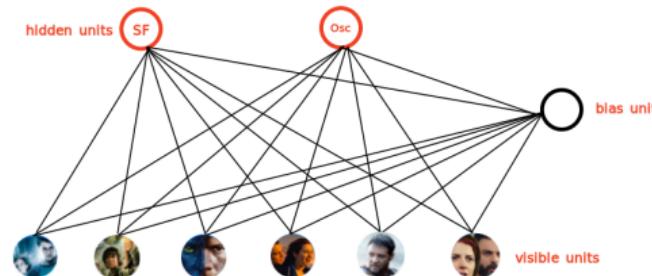
- ▶ 2. Update the **states** of the **hidden neurons**.

- Compute $a(h_j) = \sum_i w_{ij} v_i$ for each **hidden neuron** h_j .
- Set h_j to 1 with probability $p(h_j) = \text{sigmoid}(a(h_j)) = \frac{1}{1+e^{-a(h_j)}}$



RBM Example (8/10)

- ▶ 2. Update the **states** of the **hidden neurons**.
 - Compute $a(h_j) = \sum_i w_{ij} v_i$ for each **hidden neuron** h_j .
 - Set h_j to 1 with probability $p(h_j) = \text{sigmoid}(a(h_j)) = \frac{1}{1+e^{-a(h_j)}}$
- ▶ 3. For each edge e_{ij} , compute **positive**(e_{ij}) = $v_i \times h_j$
 - I.e., for each **pair of neurons**, measure whether they are **both on**.



RBM Example (9/10)

- ▶ 4. Update the **state** of the **visible neurons** in a similar manner.



RBM Example (9/10)

- ▶ 4. Update the **state** of the **visible neurons** in a similar manner.
 - We denote the updated visible neurons with v'_i .
 - Compute $a(v'_i) = \sum_j w_{ij} h_j$ for each **visible neuron** v'_i .



RBM Example (9/10)

- ▶ 4. Update the **state** of the **visible neurons** in a similar manner.
 - We denote the updated visible neurons with v'_i .
 - Compute $a(v'_i) = \sum_j w_{ij} h_j$ for each **visible neuron** v'_i .
 - Set v'_i to 1 with probability $p(v'_i) = \text{sigmoid}(a(v'_i)) = \frac{1}{1+e^{-a(v'_i)}}$



RBM Example (9/10)

- ▶ 4. Update the **state** of the **visible neurons** in a similar manner.
 - We denote the updated visible neurons with v'_i .
 - Compute $a(v'_i) = \sum_j w_{ij} h_j$ for each **visible neuron** v'_i .
 - Set v'_i to 1 with probability $p(v'_i) = \text{sigmoid}(a(v'_i)) = \frac{1}{1+e^{-a(v'_i)}}$
- ▶ 5. Update the **hidden neurons** again similar to step 2. We denote the **updated hidden neurons** with h'_j .



RBM Example (9/10)

- ▶ 4. Update the **state** of the **visible neurons** in a similar manner.
 - We denote the updated visible neurons with v'_i .
 - Compute $a(v'_i) = \sum_j w_{ij} h_j$ for each **visible neuron** v'_i .
 - Set v'_i to 1 with probability $p(v'_i) = \text{sigmoid}(a(v'_i)) = \frac{1}{1+e^{-a(v'_i)}}$
- ▶ 5. Update the **hidden neurons** again similar to step 2. We denote the **updated hidden neurons** with h'_j .
- ▶ 6. For each edge e_{ij} , compute $\text{negative}(e_{ij}) = v'_i \times h'_j$



RBM Example (10/10)

- ▶ 7. Update the weight of each edge e_{ij} .

$$w_{ij} = w_{ij} + \eta(\text{positive}(e_{ij}) - \text{negative}(e_{ij}))$$



RBM Example (10/10)

- ▶ 7. Update the weight of each edge e_{ij} .

$$w_{ij} = w_{ij} + \eta(\text{positive}(e_{ij}) - \text{negative}(e_{ij}))$$

- ▶ 8. Repeat over all training examples.



RBM Example (10/10)

- ▶ 7. Update the weight of each edge e_{ij} .

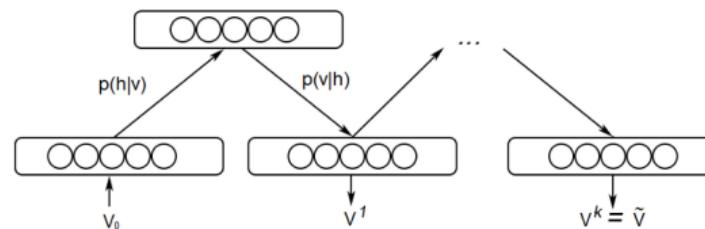
$$w_{ij} = w_{ij} + \eta(\text{positive}(e_{ij}) - \text{negative}(e_{ij}))$$

- ▶ 8. Repeat over all training examples.
- ▶ 9. Continue until the error between the training examples and their reconstructions falls below some threshold or we reach some maximum number of epochs.



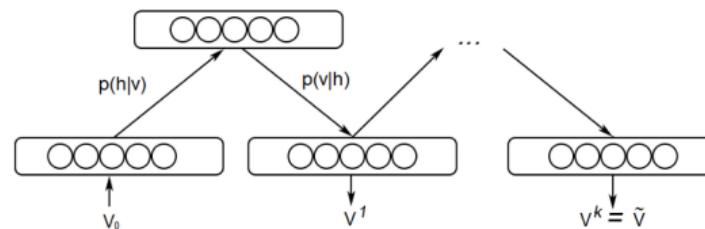
RBM Training (1/2)

- ▶ Step 1, Gibbs sampling: what we have done in steps 1-6.



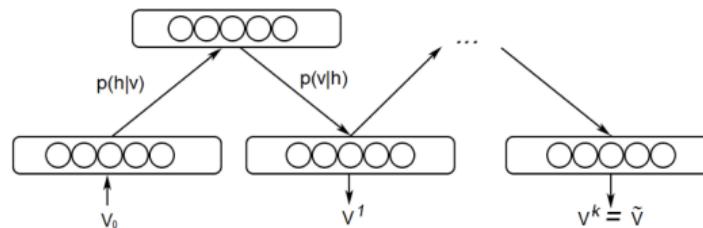
RBM Training (1/2)

- ▶ Step 1, Gibbs sampling: what we have done in steps 1-6.
- ▶ Given an input vector v , compute $p(h|v)$.



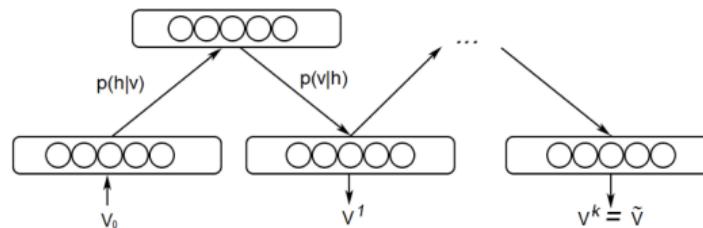
RBM Training (1/2)

- ▶ Step 1, Gibbs sampling: what we have done in steps 1-6.
- ▶ Given an input vector v , compute $p(h|v)$.
- ▶ Knowing the hidden values h , we use $p(v|h)$ for prediction of new input values \tilde{v} .



RBM Training (1/2)

- ▶ Step 1, Gibbs sampling: what we have done in steps 1-6.
- ▶ Given an input vector v , compute $p(h|v)$.
- ▶ Knowing the hidden values h , we use $p(v|h)$ for prediction of new input values v .
- ▶ This process is repeated k times.





RBM Training (2/2)

- ▶ Step 2, **contrastive divergence**: what we have done in step 7.
 - Just a fancy name for **approximate gradient descent**.

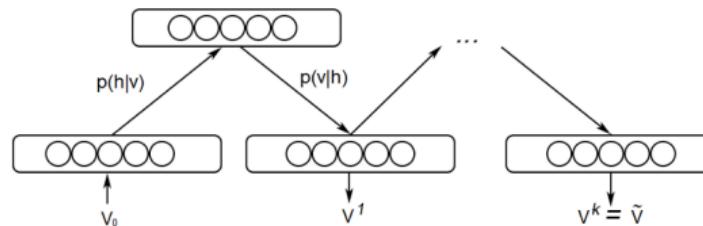
RBM Training (2/2)

- ▶ Step 2, **contrastive divergence**: what we have done in step 7.
 - Just a fancy name for **approximate gradient descent**.

$$\text{positive}(\mathbf{e}) = \mathbf{v}_0 \times p(\mathbf{h}_0 | \mathbf{v}_0)$$

$$\text{negative}(\mathbf{e}) = \mathbf{v}_k \times p(\mathbf{h}_k | \mathbf{v}_k)$$

$$\mathbf{w} = \mathbf{w} + \eta(\text{positive}(\mathbf{e}) - \text{negative}(\mathbf{e}))$$



RBM Training (2/2)

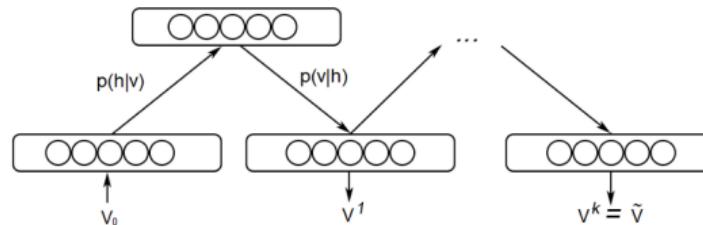
- ▶ Step 2, **contrastive divergence**: what we have done in step 7.
 - Just a fancy name for **approximate gradient descent**.

$$\text{positive}(\mathbf{e}) = \mathbf{v}_0 \times p(\mathbf{h}_0 | \mathbf{v}_0)$$

$$\text{negative}(\mathbf{e}) = \mathbf{v}_k \times p(\mathbf{h}_k | \mathbf{v}_k)$$

$$\mathbf{w} = \mathbf{w} + \eta(\text{positive}(\mathbf{e}) - \text{negative}(\mathbf{e}))$$

- ▶ \mathbf{v}_0 is the **original input**, and \mathbf{v}_k is the **input after k iterations**.





More Details about RBM



Energy-based Model (1/3)

- ▶ Energy a quantitative property of physics.

Energy-based Model (1/3)

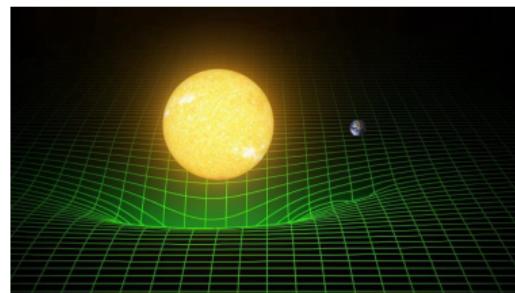
► **Energy** a quantitative property of **physics**.

- E.g., **gravitational energy** describes the potential **energy** a **body with mass** has in relation to **another massive object** due to **gravity**.



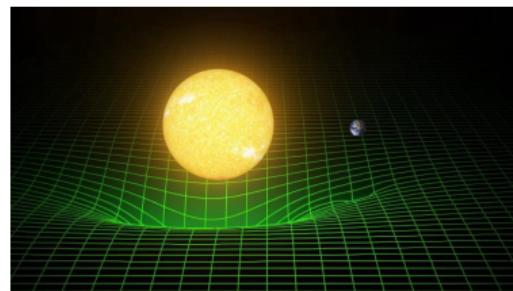
Energy-based Model (2/3)

- ▶ One purpose of deep learning models is to **encode dependencies between variables**.



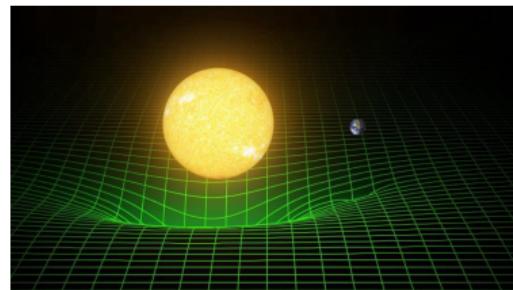
Energy-based Model (2/3)

- ▶ One purpose of deep learning models is to **encode dependencies between variables**.
- ▶ The capturing of **dependencies** happen through associating of a **scalar energy** to each **state of the variables**.
 - Serves as a **measure of compatibility**.



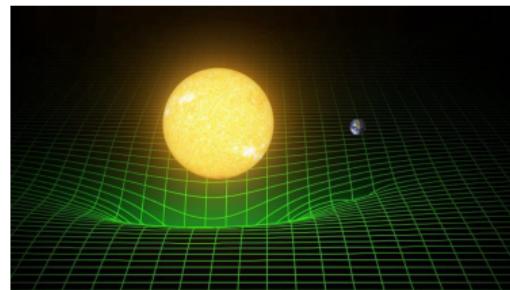
Energy-based Model (2/3)

- ▶ One purpose of deep learning models is to **encode dependencies between variables**.
- ▶ The capturing of **dependencies** happen through associating of a **scalar energy** to each **state of the variables**.
 - Serves as a **measure of compatibility**.
- ▶ A **high energy** means a **bad compatibility**.



Energy-based Model (2/3)

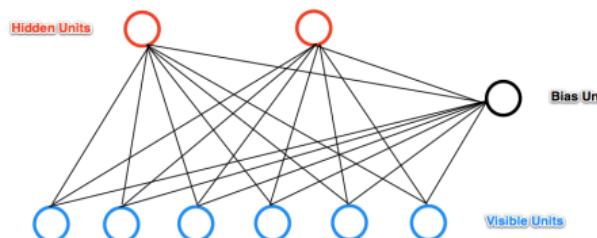
- ▶ One purpose of deep learning models is to **encode dependencies between variables**.
- ▶ The capturing of **dependencies** happen through associating of a **scalar energy** to each **state of the variables**.
 - Serves as a **measure of compatibility**.
- ▶ A **high energy** means a **bad compatibility**.
- ▶ An **energy based model** tries always to **minimize** a predefined energy function.



Energy-based Model (3/3)

- The **energy function** for the RBMs is defined as:

$$E(\mathbf{v}, \mathbf{h}) = -\left(\sum_{ij} w_{ij} v_i h_j + \sum_i b_i v_i + \sum_j c_j h_j\right)$$

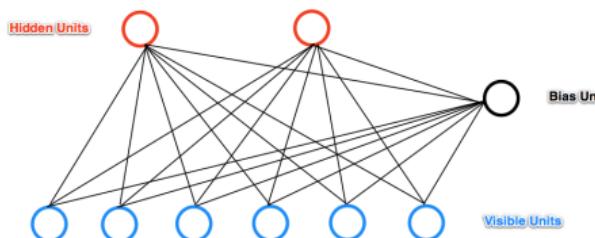


Energy-based Model (3/3)

- ▶ The **energy function** for the RBMs is defined as:

$$E(\mathbf{v}, \mathbf{h}) = -\left(\sum_{ij} w_{ij} v_i h_j + \sum_i b_i v_i + \sum_j c_j h_j\right)$$

- ▶ **v** and **h** represent the **visible** and **hidden** units, respectively.

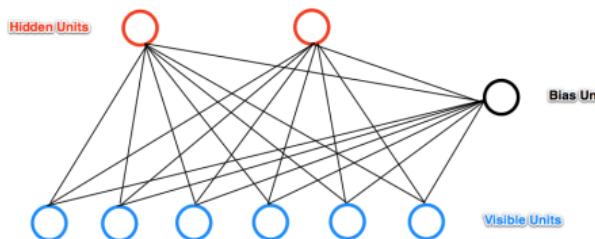


Energy-based Model (3/3)

- ▶ The **energy function** for the RBMs is defined as:

$$E(\mathbf{v}, \mathbf{h}) = -\left(\sum_{ij} w_{ij} v_i h_j + \sum_i b_i v_i + \sum_j c_j h_j\right)$$

- ▶ **v** and **h** represent the **visible** and **hidden** units, respectively.
- ▶ **w** represents the **weights** connecting visible and hidden units.

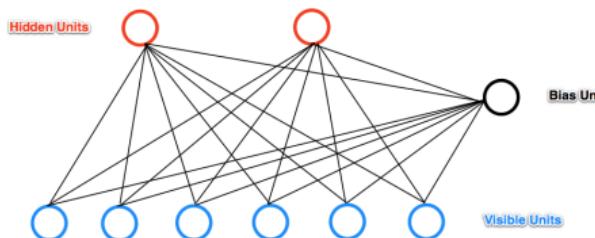


Energy-based Model (3/3)

- ▶ The **energy function** for the RBMs is defined as:

$$E(\mathbf{v}, \mathbf{h}) = -\left(\sum_{ij} w_{ij} v_i h_j + \sum_i b_i v_i + \sum_j c_j h_j\right)$$

- ▶ **v** and **h** represent the **visible** and **hidden** units, respectively.
- ▶ **w** represents the **weights** connecting visible and hidden units.
- ▶ **b** and **c** are the **biases** of the visible and hidden layers, respectively.





RBM Is A Probabilistic Model (1/2)

- ▶ In physics, the joint distribution $p(\mathbf{v}, \mathbf{h})$ is known as the **Boltzmann Distribution** or **Gibbs Distribution**.



RBM Is A Probabilistic Model (1/2)

- ▶ In physics, the joint distribution $p(\mathbf{v}, \mathbf{h})$ is known as the **Boltzmann Distribution** or **Gibbs Distribution**.
- ▶ It gives the **probability** that the system will be in a **certain state** as a function of that state's **energy**.



RBM Is A Probabilistic Model (1/2)

- ▶ In physics, the joint distribution $p(\mathbf{v}, \mathbf{h})$ is known as the **Boltzmann Distribution** or **Gibbs Distribution**.
- ▶ It gives the **probability** that the system will be in a **certain state** as a function of that state's **energy**.
- ▶ As in Physics we assign a **probability** to observe a **state** of **v** and **h**, that depends on the overall **energy** of the model **E**.



RBM Is A Probabilistic Model (1/2)

- ▶ In physics, the joint distribution $p(\mathbf{v}, \mathbf{h})$ is known as the **Boltzmann Distribution** or **Gibbs Distribution**.
- ▶ It gives the **probability** that the system will be in a **certain state** as a function of that state's **energy**.
- ▶ As in Physics we assign a **probability to observe a state** of \mathbf{v} and \mathbf{h} , that depends on the overall **energy of the model E**.
- ▶ At each point in time the RBM is in a **certain state**.
 - The **state** refers to the **values of neurons** in the visible and hidden layers \mathbf{v} and \mathbf{h} .

RBM is a Probabilistic Model (2/2)

- ▶ The probability of a **certain state** of **v** and **h**:

$$p(v, h|w) = \frac{e^{-E(v,h)}}{\sum_{v,h} e^{-E(v,h)}}$$

RBM is a Probabilistic Model (2/2)

- ▶ The probability of a **certain state** of **v** and **h**:

$$p(v, h|w) = \frac{e^{-E(v, h)}}{\sum_{v, h} e^{-E(v, h)}}$$

- ▶ The probability that the network assigns to a **visible vector v**, is given by **summing over all possible hidden vectors h**.

$$p(v|w) = \frac{\sum_h e^{-E(v, h)}}{\sum_{v, h} e^{-E(v, h)}}$$



Learning in Boltzmann Machines (1/2)

- ▶ RBMs try to learn a probability distribution from the data they are given.



Learning in Boltzmann Machines (1/2)

- ▶ RBMs try to learn a probability distribution from the data they are given.
- ▶ Given a training set of state vectors v , learning consists of finding parameters w of $p(v, h)$, in a way that the training vectors have high probability $p(v)$.

$$p(v|w) = \frac{\sum_h e^{-E(v,h)}}{\sum_{v,h} e^{-E(v,h)}}$$



Learning in Boltzmann Machines (1/2)

- ▶ RBMs try to learn a probability distribution from the data they are given.
- ▶ Given a training set of state vectors v , learning consists of finding parameters w of $p(v, h)$, in a way that the training vectors have high probability $p(v)$.

$$p(v|w) = \frac{\sum_h e^{-E(v,h)}}{\sum_{v,h} e^{-E(v,h)}}$$

- ▶ Use the maximum-likelihood estimation.

Learning in Boltzmann Machines (1/2)

- ▶ RBMs try to learn a probability distribution from the data they are given.
- ▶ Given a training set of state vectors \mathbf{v} , learning consists of finding parameters \mathbf{w} of $p(\mathbf{v}, \mathbf{h})$, in a way that the training vectors have high probability $p(\mathbf{v})$.

$$p(\mathbf{v}|\mathbf{w}) = \frac{\sum_{\mathbf{h}} e^{-E(\mathbf{v}, \mathbf{h})}}{\sum_{\mathbf{v}, \mathbf{h}} e^{-E(\mathbf{v}, \mathbf{h})}}$$

- ▶ Use the maximum-likelihood estimation.
- ▶ For a model of the form $p(\mathbf{v})$ with parameters \mathbf{w} , the log-likelihood given a single training example \mathbf{v} is:

$$\log p(\mathbf{v}|\mathbf{w}) = \log \frac{\sum_{\mathbf{h}} e^{-E(\mathbf{v}, \mathbf{h})}}{\sum_{\mathbf{v}, \mathbf{h}} e^{-E(\mathbf{v}, \mathbf{h})}} = \log \sum_{\mathbf{h}} e^{-E(\mathbf{v}, \mathbf{h})} - \log \sum_{\mathbf{v}, \mathbf{h}} e^{-E(\mathbf{v}, \mathbf{h})}$$



Learning in Boltzmann Machines (2/2)

- ▶ The **log-likelihood gradients** for an RBM with **binary units**:

$$\frac{\partial \log p(\mathbf{v}|\mathbf{w}_{ij})}{\partial w_{ij}} = \text{positive}(e_{ij}) - \text{negative}(e_{ij})$$

Learning in Boltzmann Machines (2/2)

- ▶ The **log-likelihood gradients** for an RBM with **binary units**:

$$\frac{\partial \log p(\mathbf{v}|\mathbf{w}_{ij})}{\partial w_{ij}} = \text{positive}(e_{ij}) - \text{negative}(e_{ij})$$

- ▶ Then, we can **update** the weight **w** as follows:

$$w_{ij}^{(\text{next})} = w_{ij} + \eta(\text{positive}(e_{ij}) - \text{negative}(e_{ij}))$$



IT'S OVER

IT'S FINALLY OVER

makeameme.org



Summary



Summary

- ▶ Autoencoders
 - Stacked autoencoders
 - Denoising autoencoders
 - Variational autoencoders
- ▶ Restricted Boltzmann Machine
 - Gibbs sampling
 - Contrastive divergence



Reference

- ▶ Ian Goodfellow et al., Deep Learning (Ch. 14, 20)
- ▶ Aurélien Géron, Hands-On Machine Learning (Ch. 17)



Questions?